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# SUSTAINABLE MATERIALS: AN EMPIRICAL STUDY ON THE THERMAL PERFORMANCE OF PLASTIC-BOTTLE-WALLS


Fig 1: Bottle walls building Process

WHICH ARE YOUR ARCHITECTURAL (R)SOLUTIONS TO THE SOCIAL, ENVIRONMENTAL AND ECONOMIC CHALLENGES OF TODAY?

**Research summary**

A sustainable material achieves a number of goals; they promote ecological protection, low pollution, and conservation of resources. This is achieved through some characteristics; three of which are; low waste, local sourcing, and thermal performance. The current construction industry dynamics is embracing the use of non-sustainable materials; this is clear in the rare occasions in which bottle buildings are constructed throughout the world. In fact they are only sought in poor regions with no access to high technology, or very rarely in modern cities. This has led to shortage of information, and very rare thermal performance assessments of low-tech construction generally, and plastic bottle-walls specifically. This research discusses empirically the thermal performance of sand filled plastic-bottle-walls in the Mediterranean climate of Alexandria (Egypt). Methods include literature review, and a case study test in which a chamber is constructed in the outskirts of Alexandria. The chamber walls are constructed of used plastic bottles, filled with locally sourced sand. The Research shows that sand filled plastic bottles have great thermal delay that averages over 6 hours, and promote a cooler indoor environment.

**Keywords: Plastic bottles, Building with re-used bottles, Thermal performance**

## 1. Introduction

Typical buildings are usually constructed from bricks, concrete, steel or wood, and thermal protection is assured with expanded polystyrene, mineral wool or polyurethane foam. These materials improve thermal performance of a building, but require large quantities of virgin materials, energy, and are usually expensive. Therefore shaping a general tendency to replace these materials with other ones, more economical, derived from wastes, or in other words re-used materials, would address a few of the challenges facing many countries now a-days. In light of such problem, we conduct an empirical tests to assess the thermal performance of sand filled plastic bottle constructed chamber in the Alexandria environment.

The use of plastic bottles is a way of reducing waste and reducing exploiting virgin materials. The experiment conducted is self-funded, and its results are provided as part of MSc degree at the AASTMT of Alexandria, Egypt.

## 2. Research objectives

The purpose of building with reused material is to help reduce the amount of virgin material that is used in manufacturing processes. Another purpose is to help solve the problem of managing everyday waste, thus aiming to a more sustainable community. The idea behind filled plastic bottle construction has three benefits; firstly is to reuse plastic, especially PET (polyethylene terephthalate) bottles, that are difficult to decompose, secondly is to low cost construction method, and thirdly to ensure better thermal performance due to the use of local earth material (local unprocessed sand).

## 3. Literature Review

According to (Chavez, 2005) past studies have demonstrated that the utility of PET, -as a fundamental building material- *"is a promising approach that can diminish development costs and provide numerous advantages."* And also as stated by (Silva et al, 2005) there is a 40% reduction of total cost in the economic analysis conducted for a prototype house, using recycling plastic PET bottle panels on walls and roof. They also provide agreeable comfortable conditions to inhabitants during different seasons within the chosen location of the project, while reducing the housing deficit in the country. As expressed by (Saxena & Singh, 2013) *'It is expected that by utilizing PET bottles in construction recycled materials, thermal comfort can be achieved'.* (Hansanuwat, et al., 2006) agree with previous studies indicating that utilising low-cost, locally available and recycled materials, could achieve thermal comfort can be achieved in very low cost housing.

## 4. Problem Definition

It is important to identify how Sustainable Materials perform thermally, and according to the Egyptian National Cleaner Production Center, about 20% of the post-consumer plastic bottles are being collected for recycling, and a growing percentage of the collected bottles are exported to Asia (ENCPC, 2013) Also a previous study done by (Zayani, 2010) stated that plastics composed only 12% of the post-consumer waste percentage. Hence in only three years the increase in plastic waste rose by 8%. In Egypt the lack of awareness about recycling, reuse and the general principles of sustainable living is leading the market to ignore these principles in the building industry. It is hoped that this research could provide some insights in the Egyptian market to the benefits of mixing local and reused materials in buildings.

## 5. Sustainable Materials

Sustainable building materials can be characterised as locally delivered and sourced, have low transport expenses and environmental impact, have good thermal efficiency, provide habitants needs and well-being, financially rewarding, Recyclable, have low waste and pollution generated in the manufacturing process, consume less energy in the manufacturing and production process, Use of renewable resources and assets, have low toxic discharge produced by the product, and low maintenance costs. *'It is imperative to utilise nearby and natural building materials that minimise transport and assembling vitality and air pollution. This likewise creates local employment.'* (Roux & Alexander, 2009). Due to the low thermal and electrical conductivity of plastic bottles; they are widely used for insulation purposes, High corrosion resistance, low degradation rates, and are highly durable, low-cost materials (Farag, et al., 2008). Construction materials are the gate through which temperature and relative humidity penetrate through to the building's indoor environment. Studies have highlighted the importance of the earth, as an ancient eco-friendly building material, able to keep constant indoor temperature and relative humidity values (Liuzzi & Stefanizzi, 2011). This strategy of design and construction is similar to rammed earth construction; yet the physical characteristics of sand (Local material) prevent the construction of vertical walls when compared to the soil used in rammed earth architecture. Also the utility of plastic bottles is considered a synergy as it provides a sustainable mean of waste control.

Hence understanding the different manners of heat transfer across a building is required in order to assess the thermal performance of a building material, and to better enhance the thermal comfort within a building to further enhance the well-being of inhabitants.

## 6. Thermal Characteristics of Materials

Heat is transferred due to the material's attempt to achieve thermal equilibrium with its surroundings. The flow continues until material reaches temperature equilibrium. Heat transfer happens through three mechanisms that can either operate alone or in combination; Conduction, Convection and Radiation. (Autodesk Sustainability Workshop, n.d.)

### *6.1 Appropriate Use of Thermal Mass*

Thermal mass is considered as the ability or capacity of a material to absorb heat energy. The higher the density or thickness of a material, the more heat energy would be required to alter, or completely change, its temperature (Paul Arnold Architects, 2010).Through the correct application of thermal mass internal temperatures are directed by averaging the day/ night extremes. This increases comfort and reduces energy costs (Hendler & Thompson-Smeddle, 2009).The suitable utility of thermal mass can delay heat flow through the building envelope by as much as 10 to 12 hours creating a warmer house around evening time in winter and a cooler house amid the day in summer. (Department of Local Government and Housing, 2007).

### *6.2 Conduction*

It is the transfer of heat from one body to another when in physical contact. The direction of flow will be from the warm area to the cool area. Thermal conductivity is the rate of heat flow - a factor which is determined by the ability of the molecules within a material to conduct heat (Autodesk Sustainability Workshop, n.d.). Fourier's law the basic equation of heat conduction through any element such as roof, wall or floor under steady state can be written as Equation (1) and the basic equation of Newton’s Law of cooling is expressed in Equation (2) as follows;

$$Q_{CONDUCTION} = \frac{k.A.(\Delta T)}{L} \quad (1)$$

$$Q_{CONDUCTION} = A.U.\Delta T \quad (2)$$

Where:

$Q_{conduction}$ = quantity of heat flow (W)

k = thermal conductivity of the material (W/m-K), U = thermal transmittance (W/ $m^2$- K)

A = surface area ($m^2$), L = thickness (m)

$\Delta T$ = difference between peak Temperatures

For a given temperature difference, the higher the thermal conductivity of a material of fixed thickness and cross-sectional area, the greater is the quantity of heat transferred. (Autodesk Sustainability Workshop, n.d.)

*6.3 Thermal Transmittance (Heat – U-Value)*

Thermal transmittance - better known as the U value - is the rate of transfer of heat (in watts) through one square meter of a structure divided by the difference in temperature across the structure. The lower the thermal conductivity value of a composite wall, the better its insulating properties. The thermal resistance (R) of a material and thermal transmittance (U) of a building construction can be calculated by using material thicknesses and thermal conductivity values. This value is obtained as reciprocal of the sum of all the respective thermal resistances (R) of the component materials and the internal and external surfaces resistances, it is expressed as W / $m^2$K equation (3) (Paroc Group, 2014)

$$U = \frac{1}{Si+R1+R2R+R3+..Rm+Rse} \quad (3)$$

*6.4 Thermal Resistance (R-Value)*

Thermal resistance is expressed as $m^2$ K/W. The greater the value, the more effective the material’s insulation. (Paroc Group, 2014)

*6.5 Convection and Radiation*

Convection refers to heat being transferred by movement of usually air in buildings. Heat can also be transferred through air from one body to another by radiation. In the empirical tests discussed in this research; the effect of convection, and radiation is ignored, as the tests are focused on the effect of the filled bottles on transferring heat through conduction.

## 7. Climatic Data

In Egypt the extreme sensitivity to changes in temperature caused an increase in electricity consumption to put up with necessary cooling loads; this is evident in the fact that the number of air conditioners used in Egypt has risen from 700,000 in 2006 to 3 million in 2010. Air conditioners consume around 12 % of the maximum productive capacity of power stations; resulting in a total consumption of 22% of Egypt's overall energy production in the building sector (Ministry of Electricity and Energy, 2011). These energy needs could be minimised by an intelligent choice of envelope materials. (Attial & Wanas, 2012)

## 8. Test Description

A testing chamber is built, in Burj Al-Arab area, located in the outskirts of Alexandria, (Egypt) in which sand filled plastic bottles are layered to form the walls on a squared wooden plate with dimensions 2.40 x 2.40 x 0.25m. The chamber has a plywood door 0.60 x 1.50m on the west wall, and a plywood window with dimensions 0.60 x 0.60 x 0.005m on the east wall. The ceiling is a 2.00 x 2.00 x 0.20m plywood with a 20cm insulation foam on the inside and 5cm compressed insulation foam on the top. This roof assembly is used to insure that temperature measured on the inside of the wall is a direct result of walls thermal transfer (sand filled bottles) alone. Bottles are stacked one layer at a time in opposite direction, and overlap in corners. Construction foam was sprayed around opening frames, and between the bottles to ensure a sealed environment. This is to avoid external air temperature leaking between bottles, and affecting internal temperature measurements. (Figure 2).

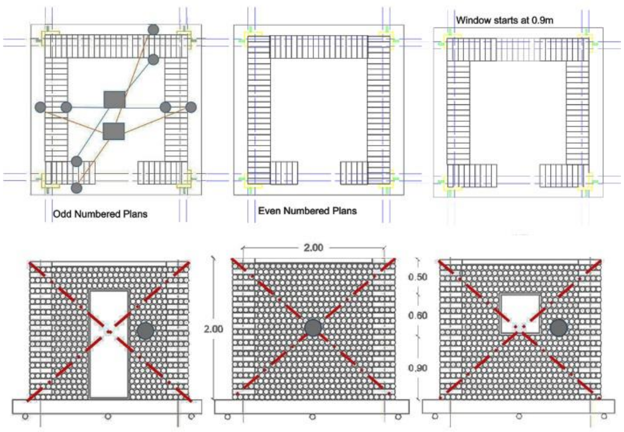


Fig 2: Drawings of test Chamber

Key:

Probe Placement

Data Logger Placement inside of chamber to insure protection from any weather conditions.

Internal Probe line External Probe line

*8.1 Data Loggers HOBO 4-Channel*

For this experiment, The HOBO UX120 Thermocouple Data Logger, a four-channel LCD data logger for measuring and recording temperature in a broad range of monitoring applications, was selected, records temperatures over a broad range (-260 to 1820$^{0}$) features an internal temperature sensor for logging ambient temperatures, Compatible with HOBOware for logger setup, graphing and analysis (Onset HOBO Data Loggers, 2014)

*8.2 Thermocouples*

Type J 6 ft Beaded Thermocouple - TC6-J Range: 0 to 250°C were used which includes 1.8m of insulated 30-AWG wire wound on an integrated spool caddy /subminiature connector. (Onset HOBO Data Loggers, 2014)

*8.3 Filling Material*

For this study; fine sand filling is used in 1.5 L, and 2L plastic bottles, reaching a total 6m$^3$ of sand. Sand was brought to the site from within the same area approximately 0.67km distance, to reduce the embodied impact and to test the role of local material on providing thermal insulation.

## 9. Results

Test was conducted for 5 days with logging intervals of 5 minutes, and results were obtained as follows; for the internal Data Logger and Probes the maximum temperature reading was 27.01°c and the minimum temperature reading was 14.32°C. As for the external probes the maximum temperature reading was 49.44°c, mostly maximum readings on the eastern wall, and the minimum temperature reading was 8.63°C. The readings shown in Figure 3, show variation on each wall. The external temperatures, as minimum and maximum, are highly above and below the comfort zone temperature range(assumed between 20°C-29°C which is a modification of the original comfort zone mentioned in the Egyptian residential energy code (EREC) of 22.2°C-25.6°C) (Mahdy & Nikolopoulou, 2013).On the other hand the internal maximum temperature shown in Figure 4 is considered within range, while the minimum internal temperature is slightly under the range stated.

Table 1 Maximum and minimum readings

| **Probe** | **Max-imum** | **Time** | **Mini-mum** | **Date-Time** |
|---|---|---|---|---|
| North External | 31.01 °C | 27/4 10:45am | 10.1° C | 25-4-5:20am |
| Internal | 25.63 °C | 26/4 5:45pm | 14.65 °C | 25-4-6:20am |
| South External | 40.94 °C | 28/4-12:30pm | 12.45 °C | 25/4-5:25am |
| Internal | 25.67 °C | 26/4-5:35pm | 14.88 °C | 25/4-5:55am |
| East External | 49.44 °C | 27/4-9:45am | 8.63° C | 25/4-5:20am |

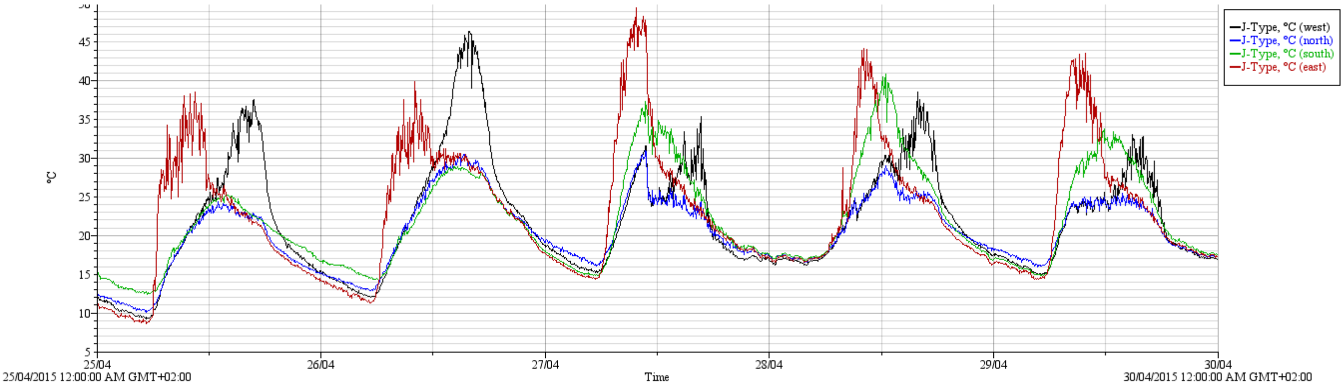


Fig 3: External walls temperature changes

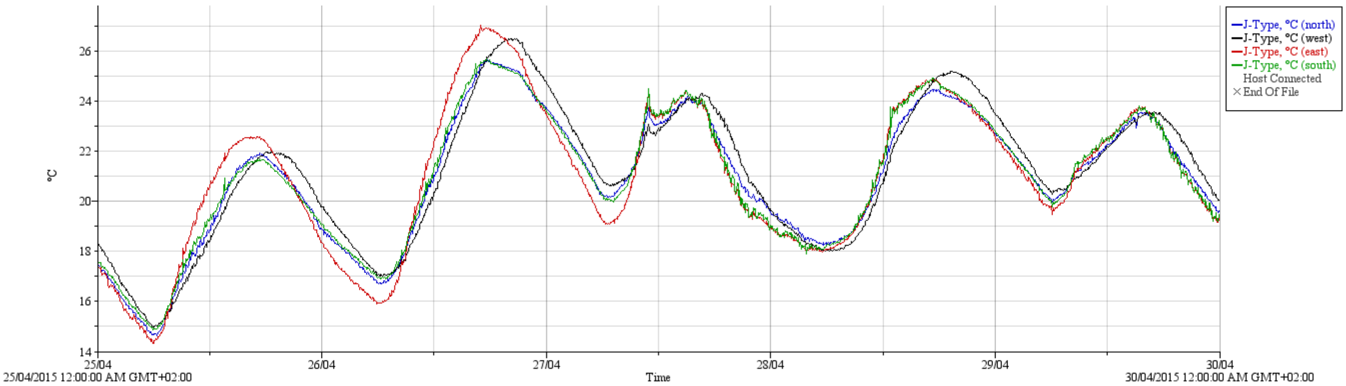


Fig 4: Internal walls temperature changes

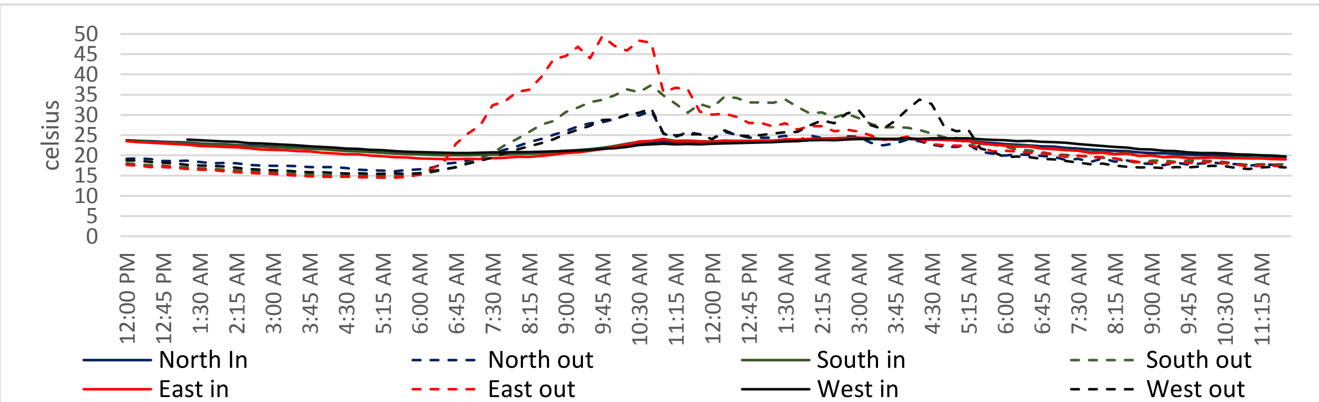


Fig 5: Graph shows a comparison between the temperature, External and internal surface sides of all 4 walls of the test chamber across 24 hours.

| | | | | |
|---|---|---|---|---|
| Internal | 27.02 °C | 26/4-5:00pm | 14.32 °C | 25/4-5:55am |
| West External | 46.35 °C | 26/4-3:50pm | 9.2°C | 24/4-5:15am |
| Internal | 26.49 °C | 26/4-8:35pm | 14.97 °C | 25/4-6:00am |

*9.1 Theoretical Verification*

To calculate $Q_{Conduction}$ and U-Value for walls, some numerical values have been gathered in the following tables;

Table 2 Thermal Conductivity and Resistance of Filling Material

| **Thermal conductivity (k) *W/(m K)*** | |
|---|---|
| Sand, dry | 0.15 |
| Polyurethane Foam | 0.03 |
| **MATERIAL** | **R-VALUE** |
| Exterior Air Film | 0.17 |
| Interior Air Film | 0.68 |
| Sand and Gravel | 0.09 |
| Polyurethane Foam | 6.25 |

(Hamdhan & Clarke, 2010) (Engineering Tool Box, n.d.) (Energy.Gov, 2015)

U-Value for all walls with reference to Table 1:

$U_{Bottles} = 1.0638$ W/m²K

$U_{Foam} = 0.1408$ W/m²K

$Q_{CONDUCTION} = 2x\Delta \mathrm{T}(U_{Bottle(0.8)} + U_{Foam(0.2)})$

$\frac{Q}{A} = \frac{K.\Delta T}{L}$ =W, A= 4m2 constant for all walls, also temperatures used derived from test for each wall separately at the time maximum outdoor temperature reached, and associated indoor temperature;

**North wall:** Δ T = (305.16-297.46= 7.7k)

$Q_{CONDUCTION} = 13.5396\ W$

$Q_{CONDUCTION} = 3.234\ W$

**South wall:** Δ T = (315.09-296.48=18.61K)

$Q_{CONDUCTION} = 32.7238\ W$

$Q_{Conduction} = 7.8162\ W$

**East wall:** Δ T = (323.59-295.7=27.89K)

$Q_{CONDUCTION} = 49.0417\ W$

$Q_{Conduction\ East} = 11.7138\ W$

**West wall:** Δ T = (320.5-298.21=22.29K)

$Q_{CONDUCTION} = 39.1947\ W$

$Q_{Conduction} = 9.3618\ W$

## 12. Discussion

The tests show that 1m² of sand filled plastic bottles costs about 100 L.E (about 11.4 Euro). This number may vary according to bottle cost, and availability of free bottle collection. On the other hand 1m² of traditional brick wall buildings costs 160 L.E (18.3 Euro). Thermal time Lag between highest external and internal temperatures recorded for the 27th of April is 4.15 hours during 24 hours, for North, South, and East walls. While for the West wall a thermal lag of 12.15 hours was reported, thus creating an average delay of 8.15 hours shown in Figure 5 furthermore, the material creates thermal mass that provides cooler mornings and warmer nights Figure 5. Temperatures recorded for the internal space is fairly steady meanwhile the temperatures recorded from the external walls surfaces, show high fluctuations. Hence promoting sand filled plastic bottles as a candidate sustainable construction material, nevertheless aesthetic wise is not quite appealing to the eye, and might need to be covered with a material which may not be sustainable.

## 13. Conclusion

The results concluded verify the possibility of using sand filled plastic bottles as a construction material, while achieving thermal lag of an average of six and a half hours, (maximum 18 hours, and minimum 1 hour), and within the confinements of the chamber temperature is within the comfort range, creating thermal mass which provides cooler mornings and warmer evenings. An average 33.6249W of thermal conductivity within a medium, and 8.0314W within the material, is concluded for all walls within the time period of 5 days.

## 14. Acknowledgments

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